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Research of features of structure formation in case of surface steel hardening

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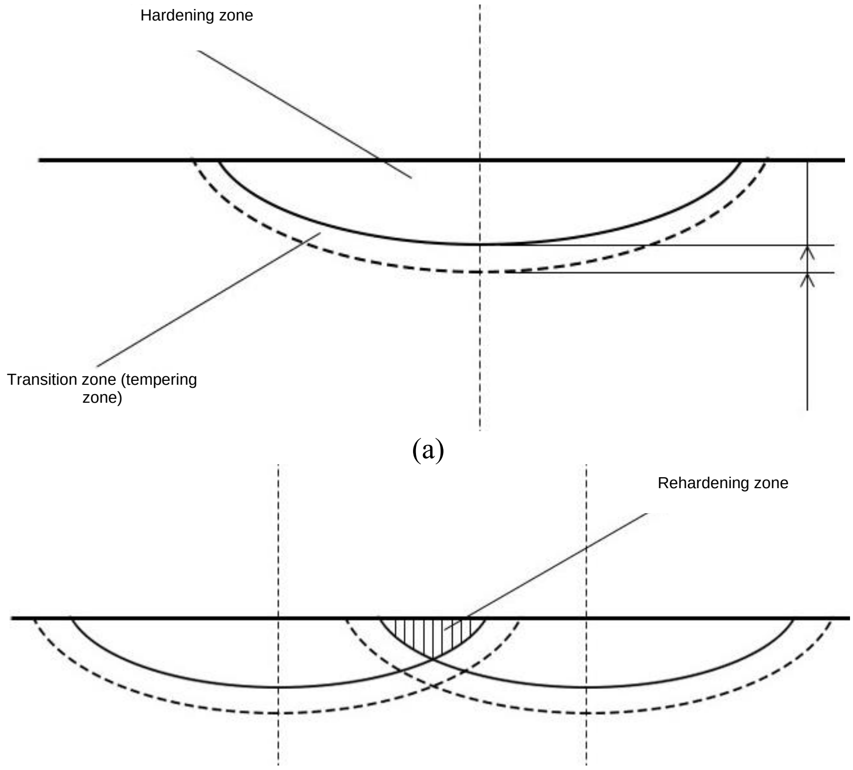
Abstract. The geometric characteristics, microhardness and features of structure formation were studied in the heat-affected zone during the surface hardening of 09Г2, 20ФЛ, 45ХНМ, 65Г steels with direct current electric arc in argon. It is shown that the depth of zone with thermally modified structure is 0.7–1.2 mm with a tendency to decrease at maximum values of arc speed. Reheating of previously formed local hardening zone is accompanied by certain decrease in surface hardness, however, by changing the overlapping, the hardness of treated surface can be optimized with achieving of formation of regular structure. A regular gradient structure with periodically changing phase composition and microhardness is formed in the surface layer of steel that has been thermally treated with an electric arc. By changing the parameters of the processing conditions (electric arc current, speed of its movement, overlap of local hardening zones), it is possible to purposefully form a certain structural-phase state of the steel surface with properties that meet the operating conditions.

1. Introduction

The significant part of machine parts fails as a result of destruction of the most loaded surface layer during the wear under conditions of frictional contact. To increase the hardness, wear resistance and other operational properties of such parts, it is effective to use surface heat strengthening with concentrated energy sources [1–17]. In this case, physical property of metal strengthening is associated with the change in structural and phase state during the local heating of surface layers and their subsequent rapid cooling.

It should be noted that the main regularities of change in the structure and properties of iron-carbon alloys in the heat-affected zone after laser treatment are studied in most detail [1–15]. The use of electric or plasma arc as energy carrier makes it possible to increase performance of the process due to sufficiently high thermal power and heat flux density (104–106 W/cm^2) on the surface of hot spot with larger (10^{-4} against 10^{-8} cm^2) area [16, 17].

The essence of surface heat strengthening of iron-carbon alloys consists in heating of local area of part surface above the critical temperatures of phase transitions (Ac_1, Ac_3, A_{cm}) and subsequent cooling with high rate which ensures formation of hardening structures. As with usual heat treatment, the features of structural state obtained as a result of surface hardening are determined with degree of solution heat treatment of austenite during the heating, its duration and also initial alloy composition and structure. The final structural state and properties formed in the heat-affected zone after surface heating depend on the cooling rate within the temperature range of the least stability of austenite, composition and size of its grain, number of other factors determined by the parameters of thermal cycle. In this case, the effects of structure modification occurring under conditions of high-rate heating and cooling affect relatively large volumes of metal – usually the local plasma hardening zone is represented in cross section with characteristic contour of segment (Figure 1, a), 5–15 mm wide with maximum depth up to 2.5 mm which significantly exceeds the size of radiation zones.



(b)

Figure 1. Cross section scheme of local zone of surface hardening (a) and heat-treated layer obtained by sequential formation of local zones.

Depending on the chemical composition and previous heat treatment of the part, under the influence of plasma heating, gradient structure is formed on its surface in the strengthening zone which composition and properties regularly vary in depth. In general, the following characteristic layers can be distinguished in the structure of this zone [1, B]:

– melting zone formed as a result of high-rate crystallization of molten metal of the surface layer. It is usually represented by dispersed dendrites elongated perpendicular to the surface near which they degenerate into cellular structure as during the micromelting. The phase composition for steel is usually a mixture of martensite and retained austenite;

– zone of hardening from solid state with a fine-grained martensitic-austenitic structure, high microhardness (8.000–10.000 MPa), wear and crack resistance. Such properties are achieved by dispersion and increasing the local inhomogeneity of the structure of massive and plate martensite with different carbon content, increasing the density of dislocations, and preserving particles of carbide and retained austenite undissolved during heating, which helps to reduce crumbling and cracking at the breaking-in stage;

– localized hardening zone transitional to the initial structure of base metal of the part. It contains a mixture of martensite, decomposition products of austenite and martensite, elements of the initial structure of base metal not subjected to phase transitions.

In case of surface hardening of parts subjected to volume heat treatment as well as when local zones of plasma hardening are overlapped in the areas heated below temperature Ac_1, tempering zone is formed (Figure 1, a).

The overall depth, features of composition and structure of strengthening zone with gradient structure are determined by a number of factors, which accounting completeness and degree affect the results of strengthening but the specified regularities are generally preserved.

The strengthening of surface of given area is achieved by sequential formation of local hardening zones in the form of extended strips (with gap, butt or overlapping between them) at each arc pass (Figure 1, b).

In this case, the number of passes shall be minimum essential and sufficient for strengthening of given surface of the product. The quality of strengthened layer is determined by center-to-center distance or overlapping of adjacent hardening zones. When each subsequent pass forms new local zone with overlapping, in the area of preformed zone where the heating temperature exceeds Ac_3, complete phase recrystallization and rehardening take place. When center-to-center distance is greater than the half-width of local hardening zone, there is no overlapping within two adjacent hardening zones and high-speed tempering takes place in that part of preformed zone where the reheating temperature does not exceed Ac_1.

2. Methods of research

The geometric characteristics, microhardness and features of structure formation were studied in the heat-affected zone during the surface hardening of 09Г2, 20ФЛ, 45ХНМ, 65Г steels with direct current electric arc in argon. Since strengthening of surface of given area was performed during the sequential formation of local hardening zones, the overlapping of these zones was 30 or 50 % of their width.

Arc current varied within 180–330 A, the rate of its movement was 80–180 m/h. Researches of phase composition were performed using optical metallography (Neophot-2), durometry (Leizt), X-ray diffraction analysis (DRON-3.0) in cobalt K_α-radiation. The profile and width of interference lines (111) of austenite and (110) α-phase were controlled, volume fraction of phases was evaluated with respect to integrated intensity of lines. Microhardness of the structural components was determined under load of 0.78 N.

3. Results and discussion of the results

It is found that the depth of zone with thermally modified structure within the studied range of parameters of the mode is 0.7–1.2 mm with a tendency to decrease at maximum values of arc speed. The initial structure of studied steels is ferritic-pearlitic, small amount of bainitic component is found in 09Г2 steel.

On the surface of local zone of heat treatment of 09Г2, 20ФЛ steels, formation of thin (~50 μm) low-etching layer with high (50–55 %) austenite content is observed that is unexpected for low-carbon steels. If pearlite colony, when heated at high rate, completely passes to the austenitic state, the carbon content in austenite shall be at the level of 0.8 % and the total amount of fixed carbon will be (0.5×0.8 % C) ~0.4 % that significantly exceeds its content in steel.

Apparently, increase in carbon concentration is consequence of microchemical inhomogeneity arising under conditions of flash heating of surface with electric arc. In the presence of structurally free ferrite, homogenization of austenite is delayed by increasing the carbon diffusion paths through ferritic grain. Therefore, even in the thin surface layer heated almost to the melting point, processes of carbon diffusion and leveling of austenite composition do not complete and zones of concentration inhomogeneity with increased carbon content remain in place of former perlite.

The Figure 2, d shows the change in the amount of austenite within strengthening zone successively formed by four passes on the surface of 20ФЛ steel. The austenite content periodically changes, in this case minimum values correspond to the boundary regions between zones and maximum concentration reaches 50–52 %.

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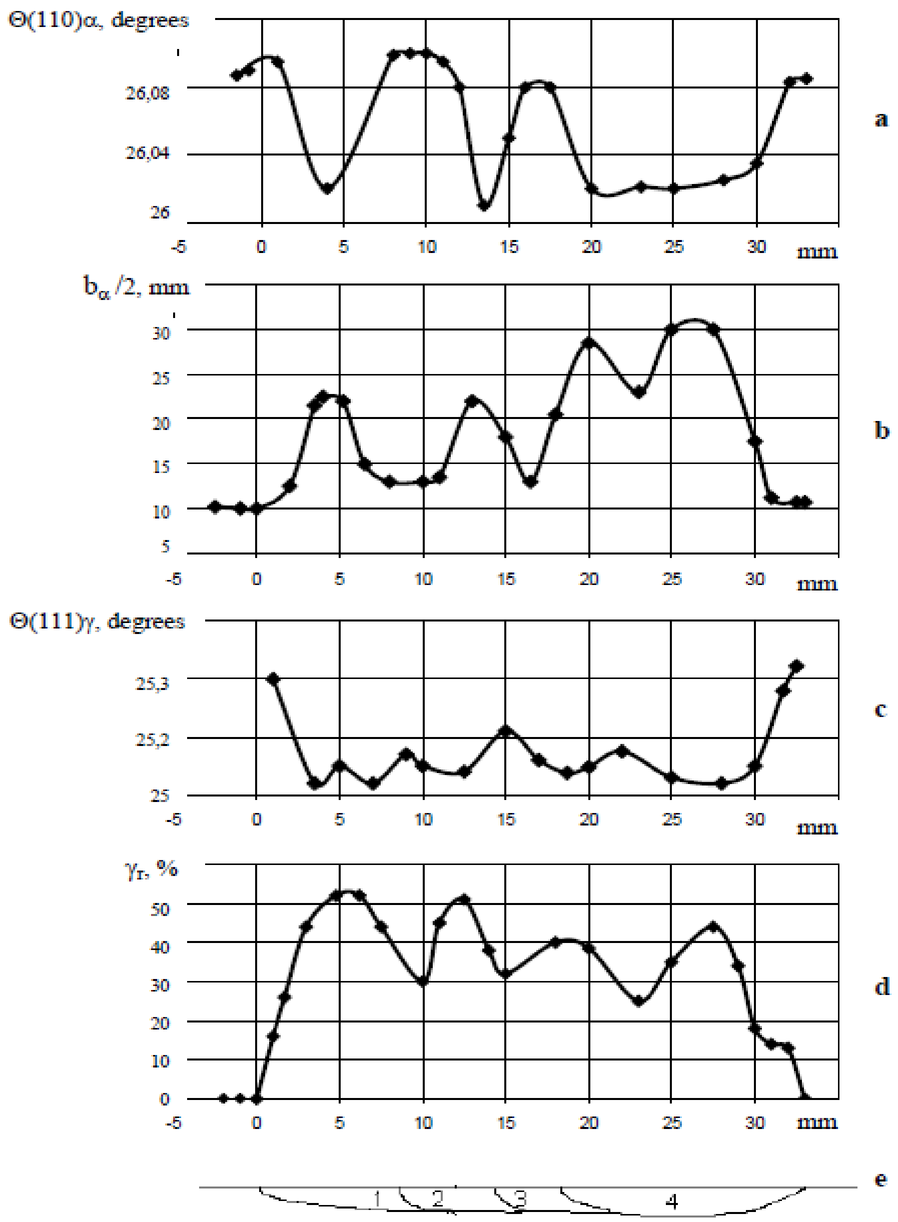

Figure 2. Change of position of interference lines of α – (a) and γ – (c) phases, half-width of line of α-phase (b), volume fraction of retained austenite γ_r (d) on the surface of 20ФЛ steel sample after arc heat treatment with sequential formation (1–4) of local hardening zones (e). Arc current is 210 A, rate of its movement is 72 m/h, overlapping of local hardening zones is 30 %.

The minimum values of reflection angle correspond to increased amounts of austenite (Figure 2, c), that is associated with the largest amount of carbon in composition of this phase. There is frequency in the change of half-width of interference lines of α-phase (Figure 2, b). The level of broadening observed in this case is consequence of not so much phase hardening as degree of tetragonal distortions of crystal lattice of this phase due to the significant amount of carbon in its composition, i. e. formation of carbon martensite. The additional fact confirming this conclusion is their displacement to the area of smaller reflection angles simultaneously with broadening of the lines associated with increase in the volume of elementary lattice (Figure 2, a).

After plasma treatment structure represented by martensite, retained austenite and carbides is formed on the surface of medium-carbon steels. The fraction of retained austenite reaches 40 % in 45XHM steel, 50 % in 65G steel (arc current is 300 A, treatment speed is 150 m/h).

When each subsequent pass forms new local zone, in the area of preformed zone where the heating temperature exceeds Ac_3, complete phase recrystallization and rehardening take place. As a result, these parts do not differ in structural composition, however, degree of dispersion of structure and depth of hardened zone increase. Microhardness is somewhat made even over the depth of zone, Figure 3, that can be explained by increase in degree of solution heat treatment of austenite over carbon as a result of increased time of retention of metal in the temperature range of existence of austenite.

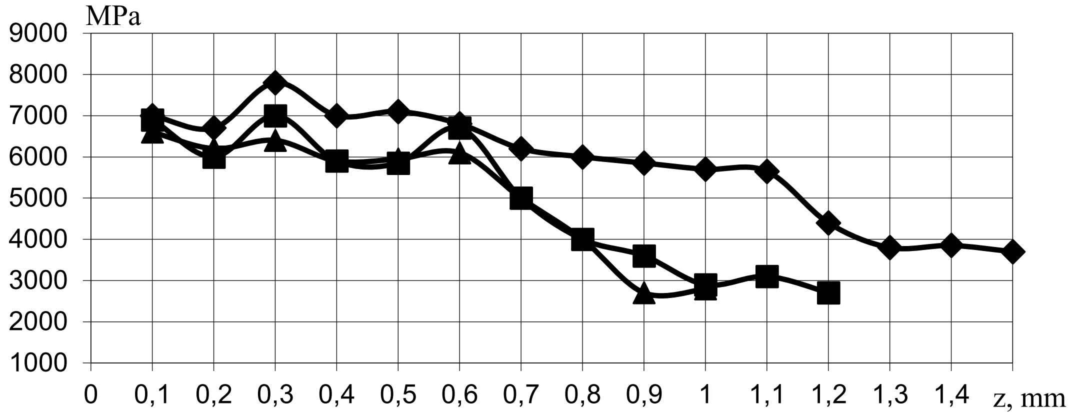

Figure 3. Change of microhardness over the depth of hardening zone (z) as a result of threefold electric-arc heat treatment of 65Г steel. Arc current strength is 300 A, arc speed is 60 m/h. The first pass is ▲, the second one is ■, the third pass is ♦.

High-speed tempering takes place in that part of preformed strengthening zone where the reheating temperature does not exceed Ac_1. Martensitic-austenitic structure of previously formed hardening zone in the areas of reheating is subject to decomposition with formation of bainitic and sorbitic structures. In place of carbon martensite particles of globular cementite are precipitated. Retained austenite of the surface layer is also partially decomposed with formation of sorbitic structure.

Since increase in treatment speed is accompanied by decrease in the specific heat flux through the treated surface, degree of solution heat treatment of austenite over carbon decreases during the heating. The martensite formed upon subsequent cooling, inheriting the microchemical inhomogeneity of austenite, has a lower carbon concentration, tetragonality and microhardness. Depth of strengthening zone also decreases. Treatment with increased heat input, when significant fraction of retained austenite is formed in the surface layer, makes it possible to obtain carbon martensite with microhardness of 6.100–8.300 MPa in the main part of strengthening zone. In this case the depth of strengthened zone reaches one millimeter.

It is known that periodic alternation of hard and soft layers can effectively increase the operational life of parts operating under dynamic and thermomechanical loads. In addition, presence of retained austenite on the surface treated with electric arc increases the incubation time of initiation and propagation of cracks, reduces the running-in time in friction pairs and allows for implementation of energy-absorbing process of its transformation to deformation martensite with partial dissipation of the fracture energy and simultaneous strain strengthening under conditions of dynamic impact of wear medium.

4. Conclusions

In a surface layer of steel heat-treated with electric arc which is formed by sequential formation of local hardening zones with certain overlapping, regular gradient structure is formed with periodically changing phase composition and microhardness.

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By changing the parameters of the processing conditions (electric arc current, rate of its movement, overlapping of local hardening zones), it is possible to purposefully form a certain structural and phase state of steel surface with properties that meet the operating conditions.

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